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Energy saving latent heat storage and environmental friendly humidity-controlled materials for indoor climate

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ABSTRACT

This paper reviews the development and application of energy saving latent heat storage phase change materials (PCMs) and environmental friendly humidity-controlled materials for indoor thermal management and humidity control. Based on the studies reported in the literatures, we indicated that the super-efficient and innovative micro-encapsulated form-stable composite PCM and humidity-controlled materials with high moisture absorption and desorption capacity and intelligent self-humidity-control and related key techniques are worth to be expected.

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1. Introduction

In recent years, energy shortage and environment pollution have become two major threats to the lives of humans faced by all countries throughout the world [1,2]. Under the double pressure, energy saving and environmental protection are two important aspects in that of the whole society [3]. With the rapid economic growth, increased urbanization has caused a tremendous rise of the energy consumption of buildings especially by cooling and heating in the hot summer and cold winter zones, respectively [4,5]. Data shows that the building sector contribution toward global energy consumption is about 40% [6,7]. For example, up to now, there are about 40 billion m^2 residential buildings, in which 95% are classified as non-energy-saving in China, what's more, about 70–80 million m^2 new inefficient residential and office buildings will be built each year [8,9]. The highest average heating energy consumption of building is as high as 63% [10]. Many scientists and environmentalists have devoted considerable efforts to promote energy saving in buildings continuously in the past. As it is known to us, the evolving and diverse lifestyles are demanding improved and more comfortable living environments [11]. Especially in North America and European countries, people spend 80–90% of time staying indoors and thus require more attention to improving the air quality inside buildings [12]. Therefore, heating, ventilation and air conditioning systems (HVACs) play important roles in daily life and summer and winter in particular. However, the air conditioning takes up more and more energy consumption with the high-speed development of architecture industry [13]. In addition, the

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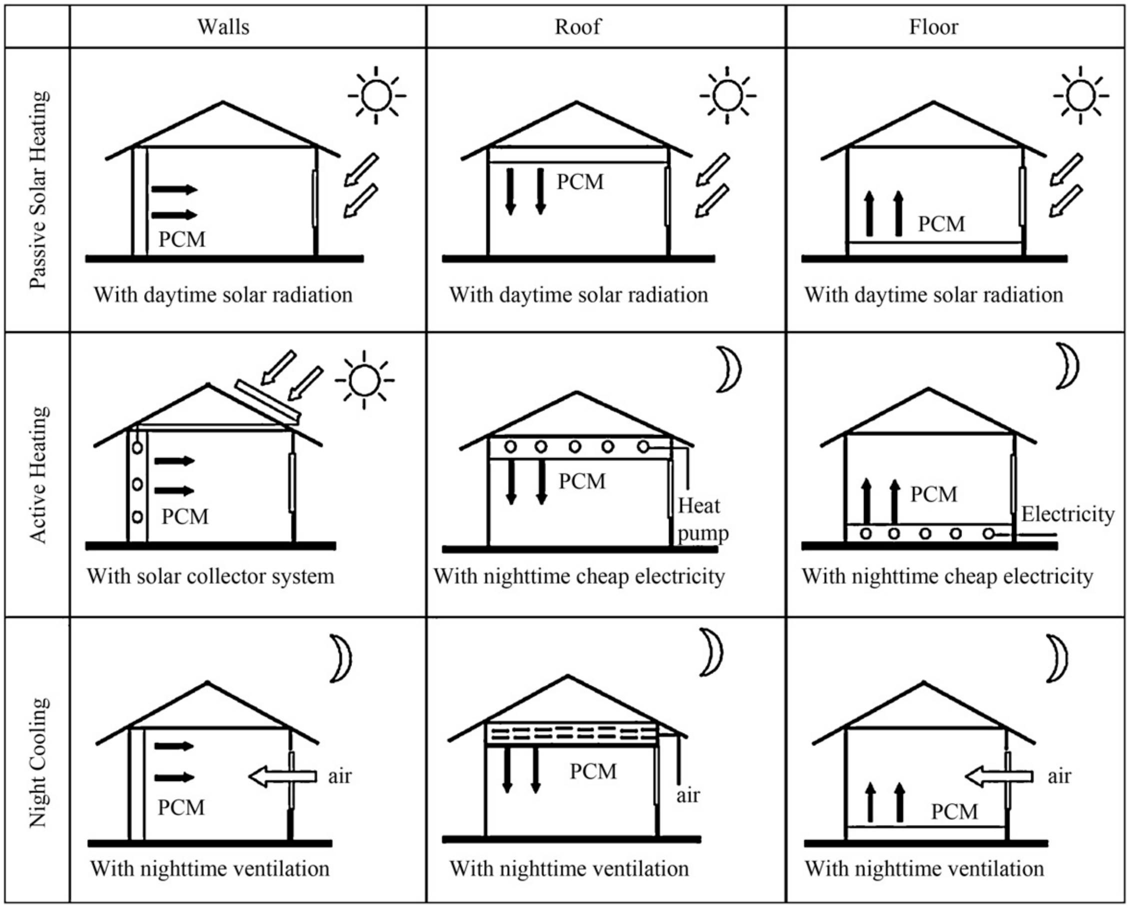

Fig. 1. The forms of PCM in building [42,54,55].

secondary contamination problems, such as biological contamination produced in the HVACs, also caused wide public concerns [14]. During harsh winter days, fossil fuel consumption used directly or indirectly for domestic space heating represents a high percentage of the total energy consumption and the combustion products increase green house gases and pollutants emitting [15]. In China, there were 66.85 million Chinese kangs used by 174.56 million populations for heating, which shared more than 80% of rural energy consumption [16]. The energy consumption with increasing trend of coal, electricity and gas requires unlimited resources are not consistent with the reality.

On the other hand, relative humidity is the key factor that determines the survival and contamination development of the indoor dust and biological [14,17]. Improving the effect of indoor environment air humidity as well as temperature to human life has been taken more and more attention. The investigation of dynamic latent heat storage undertaken on building construction and furnishings had indicated that moisture storage acted to increase cooling loads of air conditioning and then increased electrical energy consumption [18]. The discrepancy of annual heating and cooling relative variation rates is also significant under different kinds of outside air humidity [19]. Indoor humidity is related closely to health and has a great influence on the construction durability simultaneously. Low humidity environment (<30%) is associated with dryness of skin and throats, mucous membrane and sensory irritation of eyes. While high humidity environment may affect the perceptibility of air quality, lead to respiratory discomfort and allergies, contribute to the deterioration of building materials, cause mould growth, etc. [20,21]. The considerable humidity is 40–70% for keeping comfortable [22]. To control indoor humidity, the HVACs are used commonly, based on the above analysis, which will increase the energy consumption.

To prevent useless ventilation and heating, many methods have been developed and investigated to control the temperature and indoor humidity for the purpose of energy saving [23–26]; nevertheless most of them are still based on electrical energy and fossil fuel consumption. Actually, many researchers have sought to find and develop new building constructions and materials to store and release energy or humidity. In order to make buildings have the ability of absorbing and desorbing heat, a certain heat resistance and a big heat capacity of the building envelopes materials are necessary [27]. The materials such as stone, brick and concretes used for thermal control in building have been practiced for thousands of years. However, the thermal energy was stored as sensible heat so that massive amounts were required [28]. A particularly interesting research area for utilisation of renewable energy is latent heat storage [29]. The application of latent heat storage material which can be named as phase change material (PCM) in building has become a research hotspot for energy saving. The thermal energy is stored as sensible and latent heat in the PCM, in which the major proportion is latent heat because of high latent heat storage capacity. Latent heat storage is the heat absorption or release when PCM changes from solid to liquid or liquid to gas or vice versa at more or less constant temperature. The PCM can decrease HVACs load and reduce indoor temperature fluctuate, raise comfort degree, little use during summer and winter or even no use of energy consumed during intermediate seasons by heating or cooling facilities [30,4,31]. In short, building energy saving is an important aspect in energy saving field and many more works need to be done further in the future [32].

Table 1
The potential PCM can be used in building.

Nomenclature	Formula	Melting point (°C)	Latent heat (kJ/kg)
Propyl palmitate	$CH_3(CH_2)_{12}COOC_3H_7$	16–19	186
Acetic acid	CH_3COOH	16.7	184
Capric/lauric acid	45% $CH_3(CH_2)_8COOH$, 55% $CH_3(CH_2)_{10}COOH$	17–21	143
Dodecanol	$CH_3(CH_2)_{11}OH$	17.5–23.3	188.8
Butyl stearate/butyl palmitate	49/48	18–22	140
Butyl stearate	$CH_3(CH_2)_{16}COO(CH_2)_3CH_3$	18–23	140
Potassium fluoride tetrahydrate	$KF{\cdot}4H_2O$	18.5–19	231
Capric/lauric acid	82/18	19.1–20.4	147
Capric/lauric acid	61.5/38.5	19.1	132
Paraffin C_{13}–C_{24}	–	20–24	152–189
Polyethylene glycol 600	$H(OC_2H_2)_nOH$	20–25	146
Iron bromide hexahydrate	$FeBr_3{\cdot}6H_2O$	21.0	105
Dimethyl sabacate	$C_{12}H_{22}O_4$	21	120
Capric/myrstic	73.5% $CH_3(CH_2)_8COOH$, 26.5% $CH_3(CH_2)_{12}COOH$	21.4	152
Polyglycol E 600	–	22	127.2
Capric/palmitate	75.2/24.8	22.1	153
Tech. grade octadecane	$CH_3(CH_2)_{16}CH_3$	22.5–26.2	205.1
RT20/montmorillonite	–	23	79.25
Salt hydrate from climator	Climsel C23/24	23/24	148/216
Peg1000/Peg600	–	23–26	150.5
Myristic acid, acetic acid octyl ester	34%$C_{14}H_{28}O_2$ 66%$C_{10}H_{20}O_2$	24	147.7
Manganese nitrate hexahydrate	$Mn(NO_3)_2{\cdot}6H_2O$	25.8	125.9
Calcium chloride hexahydrate, magnesium chloride hexahydrate	66.6% $CaCl_2{\cdot}6H_2O$, 33.3% $Mgcl_2{\cdot}6H_2O$	25	127
Calcium chloride, magnesium chloride hexahydrate	50%$CaCl_2$, 50%$MgCl_2{\cdot}6H_2O$	25	95
1-Dodecanol	$C_{12}H_{26}O$	26	200
D-Lactic acid		26	184
RT25–RT30	–	26.6	232.0
Capric-stearate	86.6/13.4	26.8	160
Calcium chloride, sodium chloride Potassium chloride, water	48% $CaCl_2$, 4.3% NaCl, 0.4% KCl, 47.3% H_2O	26.8	188
Vinyl stearate	$C_{20}H_{38}O_2$	27–29	122
Organic PCM/silicon dioxide	–	27–30	77
Calcium chloride hexahydrate	$CaCl_2{\cdot}6H_2O$	29.7	171
Gallium–gallium antimony eutectic	–	29.8	–

In the last decades, various PCMs have been investigated widely by experiments and numerical simulation to demonstrate the possibility of being applied as building materials [6,31,33–43]. Proper use of PCM can help reduce not only energy consumption and improve indoor thermal comfort but also reduce CO_2 emissions. The research of humidity-controlled materials is widely improved as well as PCM especially in Japan because the weather of which sultry in summer and biting in winter [22]. To date most of the reviews focus on the PCMs preparation and characterization or potential application in building sweeping. Kuznik et al. [44] have presented a review of the integration of phase change materials which focus on integration and thermophysical property measurements and various experimental and numerical studies in building walls. Tyagi et al. [45] also presented a review of previous research work with thermal energy storage incorporating the phase change materials (PCMs) in the building applications but mainly focus on microencapsulation technology. It may be mentioned that in the literatures there is no comprehensive works on humidity-controlled materials in building. This paper presents a review especially relevant to the development of thermal management PCMs and humidity-controlled materials application indoor.

2. Latent heat storage phase change materials

2.1. Development of PCM and application in building thermal management

Since the first time mentioned in the 1940s, the studies of PCM received much attention especially after late 1970s and early 1980s because of the energy crisis. To date there are many reviews related to the development of PCM including the geometry and configurations, mathematical modeling, preparation and characterization, heat transfer and enhancement techniques and some applications [6,40–43,46–53]. Most studies have demonstrated that thermal storage performances of PCMs have positive effects on building thermal management. PCMs have been considered for thermal management in buildings since 1980 by implementing the PCM in gypsum board, plaster, concrete or other wall covering materials [6,40]. Some applications of PCM in building are shown in Fig. 1. The building structure and material, door and window type, air conditioning, refrigerator, and home computer, are closely related with energy consumption and thus improve the development of PCM application in building.

There are many PCMs available in any required temperature range which falls into the following three categories: inorganic, organic and metallic or metalized reflective membranes. Firstly, an appropriate PCM for building thermal management requires the PCM to have proper melting temperature range. That is, only PCMs that have a phase transition close to human comfort temperature (~20 °C) can be used [40]. The recommended melting temperature range of PCMs for building is generally between 20 and 32 °C. The possible PCMs with melting point and latent heat in the desired operating temperature range are summarized in Table 1 from the literatures [40,41,49–58].

The other main criteria of selection the PCM for indoor thermal management are: (i) available in large quantities at low cost, (ii) high latent heat, high specific heat and high thermal conductivity, (iii) Small volume changes during phase transition, (iv) little or no subcooling during freezing, (v) stability, non-poisonous, nonflammable and non-explosive, (vi) the building surrounding local climate conditions such as solar radiation and temperature fluctuations day-and-night.

After the PCMs are selected to apply in the building for the thermal management indoor, another important aspect is the

Table 2
The PCMs using in building for thermal management indoor.

Reference	Function	Thermal parameter	Dimension (m): L × W × H	Main conclusions
[71,72]	Roof	T_m: 26–28 °C	Room: 1.22 × 1.22 × 2.44 PCM: 2 × 1 × 0.0254	January: maintained constantly at 27 °C, July: approximately 4 °C higher than non-PCM room
[73]	Ceiling	T_m: 25 °C	–	The maximum thermal load was cut by 9.4% compared to conventional rock wool ceiling board
[74]	Ceiling	T_m: 18 °C	Panel: 3 × 2	Requires a significantly slower fluid flow rate, can absorb energy at a set point
[75]	Floor	–	–	Temperature fluctuation was obviously lower, room temperature was 1–2 °C higher than ordinary room
[76,77]	Floor	H_m: ~120 kJ/kg	Cabin (3 × 2 × 2) Window (1.6 × 1.5)	About 2 °C higher than the room without PCM floor, temperature swing range was obviously minimized
[78]	Floor	T_m: 17 – 22 °C	1 × 0.5 × 0.3	89% of daily cooling load could be stored in a system with 30 mm thick packed bed of the granular PCM
[79]	Floor	T_m: 15–30 °C	Experiment (3 × 2 × 2) Simulate (5 × 5 × 3)	H_m and λ should be larger than 120 kJ/kg and 0.5 W/(m K), thickness not be larger than 20 mm
[80]	Floor	T_m: 20–22 °C H_m: 172 kJ/kg	0.5 × 0.22 × 0.09	Cold stored in PCM is 732.6 kJ with the mass of PCM 3.6 kg
[81]	Floor	H_m: 150 kJ/kg	–	Energy released increased by 41.1% and 37.9% during heating and cooling
[82]	Underfloor	T_m: 18.4–23.5 °C	0.575 × 0.453 × 0.463	The novel FSPCM is a prospective material for thermal energy storage in electric floor heating systems
[83]	Underfloor	T_m: ~28 °C	Concrete slabs (0.5 × 0.5 in × 0.095)	Showed a much lower surface temperature fluctuation and maintained an acceptable surface temperature whole day by heating only 8 h
[84]	Underfloor	–	Room (3.04 × 2.77 × 2.4) Window (1.08 × 1.08)	Reduced heating energy consumption significantly (30% or more)
[85]	Underfloor	T_m: 23.5/24.9 °C H_m: 41.9 kJ/kg	Duct: 0.14 × 0.14 × 0.9 PCM: 0.14 × 0.14 × 0.3	With a reduction of ventilation load by 62.8%, 42.8–46.2% in different cities in Japan
[86]	Underfloor	T_m: 23 °C H_m: 110 J/g	Box: 1.13 × 0.725 × 0.69	Reduction of maximum floor temperatures up to 16 ± 2% and increase of minimum temperatures up to 7 ± 3%
[87]	Underfloor	T_m: 20/13.5 °C H_m: 107 ± 11/103 ± 13 J/g	Tile: 0.66 × 0.66 × 0.052	Stabilizing the room temperature and decreasing energy consumption required for thermal conditioning
[88]	Wallboard Underfloor	H_m: 62–138 kJ/kg	Room (3 × 2 × 1) Window (1.6 × 1.5)	Absorb solar energy to narrow the temperature swing in winter, PCM layer should not be thicker than 2 cm
[27]	Wallboard	T_m: 28 °C H_m: 60 kJ/kg	Thickness is set at 0.03	The energy-saving rate of heating season ŋ could get to 10% and 17%.
[89]	Wallboard	T_m: 19–24 °C	Two types of rooms was made	Reduced the fluctuation range of indoor temperature and heat flow from the outside into indoor in summer
[90]	Wallboard	Summer T_m: 24–28 °C Winter T_m: 18–20 °C	Room (4.3 × 2.97 × 2.75) Window (0.73 × 1.5) Door (0.8 × 2)	Diverted 40% of peak load in winter and reduced the peak cooling load by 25% in summer
[38]	Wallboard	T_m: 18–24 °C	Room (4.3 × 3 × 2.8) Window (1.5 × 1.5) Door (1 × 2)	The mean temperature was 1–2 °C lower than that of ordinary room and the heat flow was lowered by 4.6 W/m^2.
[91]	Wallboard	T_m: 21–25 °C H_m: 148 J/g	0.92 × 0.92 × 0.025	The efficiency was remarkable with a reduction of the indoor temperature amplitude of approximately 20 °C
[92]	Wallboard	T_m: 22 °C	Optimized the value of PCM wallboard thickness	The optimum value of the PCM varied between 9 mm and 15 mm.
[93]	Wallboard	T_m: 22 °C	3.1 × 3.1 × 2.5	Caused a decreasing in the fluctuations of about 3.5 °C for east and west walls and 2.8 °C for the north wall.
[80]	Wallboard	T_m: 13.6/23.5 °C	3.1 × 3.1 × 2.5	The air temperature in the room with PCM lowers up to 4.2 °C
[94]	Wallboard	T_m: 20.4/19.1 °C	Room (5 × 3.3 × 2.8) Window (1.5 × 1.5)	Weaken indoor air fluctuation and reduce the heat-transfer to outdoor air and keeping warmth
[95]	Wallboard	T_m: 25.5–27 °C	L × W (4.43 × 2.95), surface area 52 m^2	A reduction of the peak temperature of up to 4 K could be ascertained.
[96]	Wallboard	T_m: 26 °C H_m: 110 J/g	Room (2 × 2 × 3) Window (2, 1.7 × 0.6) Window (4, 0.751 × 0.4)	Improved thermal inertia as well as lower inner temperatures with PCMs
[41]	Wallboard	T_m: 29 °C	PCM 30% in wallboard	The surface temperature and the air temperature in the room decreased by 3.5 and 2.5 °C, respectively.
[56]	Wallboard	–	1.83 × 1.83 × 1.22	Cooling load was reduced by approximately 8.6% and 10.8% when 10% and 20% PCM was used

Table 2 (*Continued*)

Reference	Function	Thermal parameter	Dimension (m): L × W × H	Main conclusions
[97]	Wallboard	T_m: 26/28 °C	Room (2.4 × 2.4 × 2.4)	Reduce the peak temperatures up to 1 °C and smooth out the daily fluctuations
		H_m: 179 J/g	Bricks (0.9 × 0.14 × 0.075)	
[98]	Wallboard	T_m: 21.7 °C	Room (3.1 × 3.1 × 2.5)	Annual energy saving of 2.9% in air-conditioning system was achieved
[99]	Wallboard	T_m: 23 °C	Total area of SSPCM plates: 296.4 m^2	Over 11% in electricity cost reduction and over 20% in peak load reduction
	Underfloor	H_m: 160 J/g		
[100,101]	Wallboard	T_m: 23.5/13.6 °C H_m: 107.5/72.4 J/g	Room (3.55 × 5.2 × 2.7)	PCM wallboards enhance the thermal comfort of occupants
[102]	Wallboard	T_m: 29 °C	1.8 × 6 × 0.04	6–12 °C rise of plants and inside air temperature and 4–5 °C for cover temperature at night time
		H_m: 187.49 J/g		
[103]	Wallboard Ceiling	T_m: 21 °C	3.9 × 3.3 × 2.7	Saved about 47% of normal-and-peak-hour energy and 12% of total energy consumption in winter in Beijing
[57]	Gypsum board	T_m: 23 °C	0.07 × 0.07 × 0.07	The gypsum boards had a function of reducing the indoor temperature variation of the test room
		H_m: 79.25 J/g		
[33]	Gypsum board	–	2.82 × 2.22 × 2.24	Reduced maximum room temperature about 4 °C and reduced the heating load significantly
[104]	Trombe wall	T_m: 25–30 °C	Panel (0.8 × 1.8 × 0.05)	Optimal thickness of the panel (50 mm) by simulation, the efficiency of absorption was 79%.
[105]	Shutter	T_m: 49 °C	1 × 1 × 1	The heat storing capacity of the cell increases up to 4 for 4–5 h, which was used during nighttime

T_m: melting point; H_m: latent heat; λ: thermal conductivity; L × W × H: length × width × height.

incorporation of PCM and building materials or structure. Generally, direct incorporation, immersion and encapsulation are considered as the most promising methods of PCM incorporation. The initial methods were simple and at a low cost, the PCMs were impregnated directly into the wallboard or underfloor but they were inflammable owing to the leakage of the liquid PCM after several heating–cooling cycles. Therefore, it is necessary to develop novel routes for incorporating PCMs into building materials [57]. Subsequently the porous building material was dipped into the melted PCM and absorbed the PCM into the pores by capillary action. In this method, leakage may be still a problem over a period of many years. Then a new way makes the PCM impregnated into some microstructure supporting materials to prepare form-stable composite PCM, which can be called as micro-encapsulated PCM. Although some other new problems such as reaction of PCMs with supporting materials, volume variation during the phase change and low thermal conductivity, researchers have done many works to optimize the preparation and enclosure technologies and to enhance the heat transfer performance [59–67]. Based on these analysis and investigation, the micro-encapsulated PCM will attract more attention to building application.

2.2. PCM used in indoor focus on building construction

The PCM used in indoors focus on building construction for thermal management mainly including wallboards, doors and shutters, building blocks, floors and ceiling boards even roofs. Otaka and Nagata [68,69] have proposed a green roof building using lightweight soil as heat storage materials. The system can be also thought as an external structure to control indoor temperature. Ismail and Henriquez [70] analyzed the thermally effective windows with moving change material curtains. A lot of researches and applications of PCMs used in building confirmed that latent heat storage indoor is energy saving and environmental friendly. PCMs used in indoors focus on building construction including roof, ceiling, floor and underfloor heating system, wallboard, door and shutter, are summarized in Table 2. It can be seen that no matter simulation and experiment results are all well with expected effect. As the architectural styles and structures are complex, the details of the design of the whole building or indoor space are not listed in this review, but the references are listed instead for readers to look deeper.

2.3. PCMs used in indoors focus on furnishings and appliances

With the improvement of the living standard of the people, there has been a dramatic increase in the amount of household furnishings and appliances. In addition to air conditioning, the energy consumption of refrigerator is also a section which cannot be ignored. Almost 90% of the world's population use home appliances, especially refrigerators, which play important roles in improving the quality of life. In Malaysia, the number of refrigerators will be increased to about 11,293,043 in the year of 2020, which accounted for about 26.3% of electricity consumption in household [106]. In US, refrigerators are accounting for 14% of electricity consumption [107]. Therefore, the heat generation from refrigerator and the energy efficiency of refrigerator itself is very important for thermal management indoor. PCM using indoor for household refrigerators energy saving have been widely investigated. Simard and Lacroix [108] performed a PCM cold storage unit operating under frosting conditions by employing inside refrigerated compartment. A simulating model showed that the coefficient of performance was improved by 12% using PCM [109]. Azzouz et al. [110] located the PCM on the back side of the evaporator and tested with water and with a eutectic mixture (freezing point −3 °C), the results showed that the coefficient of performance significant increased by 10–30%. The schematic presentation of the refrigerator with PCM in their experiment is shown in Fig. 2. Some other furnishings and appliances such as computers can be seen as heat sources, the major question is heat dissipation especially in hot summer. At the same time the heat generated from these heat sources will increase the cold load of air conditioning. The PCMs used indoors may be considered such thermal or cold load. In some high population density areas such as major cities and campuses, a bathroom occupied a relatively smaller space. The heat generated in the human body cannot be dissipated quickly and then the PCM will be a potential selection for thermal control.

On the whole, the effective use of PCMs indoor depends on many factors mainly containing encapsulation method, location of PCMs, outside climate condition, building design and orientation, amount

Table 3
Humidity-controlled materials application in building.

Material	Reference	Preparation/method	Main conclusions
Mesostructured silica-n	[11]	Synthesized using fumed silica and quaternary alkylammonium surfactant	The maximum amount of adsorbed water content is between 40 and 90%
Sepiolite	[119]	Heat-treated in air in the temperature range of 110–500 °C	Useful as controller of humidity in environments where the relative humidity is usually very high (80–90%)
Polyacrylic acid fibers	[120]	Discussed the relation of *B*-values and moisture content	Moisture content of about 40 wt% when *B*-value = 0/ °C at 15.0 g/V
Polyacrylic acid fibers	[121]	Discussed the relation of *B*-values and moisture sorption–desorption isotherm	Fiber products having the desired *B*-value can be designed from the moisture sorption and desorption
Sepiolite and activated carbon	[122]	Mixed with sepiolite and activated carbon	Adsorbent with better humidity-controlling properties in the medium–high relative humidity range (89–39%)
Kaolinite	[123]	Prepared by a selective leaching and firing	Water absorbed increased sharply at the relative humidity in the range between 50–75%
$AlOOH–Al_2O_3$	[124]	Prepared by precipitation of aluminium chloride solution	Showed steep increase of water vapor adsorption in the relative humidity range of 55–90%
Cement, polymer gel	[125]	Mixed by saline solution, such as $CaCl_2$ or LiCl solution	The absorption and desorption rates of the hygroscopic board are 10–13 times of the conventional concrete block
Zeolite	[126]	The conversion accomplished under water vapor below saturation condition	The new synthesis method of zeolites could be general applied
Sepiolite	[115]	Mixed with phosphate, alumina and fibrin as additives	Can adsorb or desorb 1.2 g/g water at 25 °C
Porous silica gel	[127]	From water glass in the presence of poly (acrylic acid)	Equilibrium adsorption amount of water was 0.7 g per gram of silica
Porous ceramics	[128]	Mixture of volcanic ash, weathered volcanic ash, and waste glass	The absorbed water volume of GA: 255 g/m^2; GM: 55 g/m^2
Zeolitic tuff	[129]	Milled and reacted with 50 mass% of ordinary portland cement	The pore volume did the amount of water vapor adsorption and desorption
Silicon carbide, frozen skim milk	[130]	Simulate by finite difference solution	Drying time was 33.1% shorter than that of ordinary microwave freeze-drying under typical operating conditions
Porous composite	[131]	Compounded by zeolite, diatomite, sepiolite, nano-titanium dioxide	The amount of adsorbed water content was 5–6%
Silica gel, calcium chloride	[132]	Silica gel, calcium chloride and composite desiccant are compared	Composite showed a higher hygroscopic capacity and exhibited a remarkable increase in moisture removal
Polymer resin, inorganic material	[133]	A composite mixed by polymer resin and inorganic material	Composite showed a shorter hygroscopic time and could be kept a constant relative humidity (43%)
Japanese cedar flat grain wood	[114,134]	Mixed with cedar flat grain wood and porous ceramic wall materials	Changing the rate of temperature variation over one period strongly affected the C_b value
Allophane, silica gel and gibbsite	[22]	Plate sample prepared by the mixture of gibbsite and clay	Mixture was appropriate for the interior wall materials and showed superior performance
Charcoals	[23]	Prepared by carbonizing kenaf at 400–1000 °C	Humidity-control capacities were much larger than those of common wood charcoals
Activated carbons (from bambo)	[117]	Prepared by chemical activation with K_2CO_3 or physical activation with CO_2	The highest humidity control capacity was prepared at 873 K with impregnation ratio 1.0
Carboxymethyl cellulose, sepiolite, acrylic acid/acrylamide copolymer	[135]	Blending the above components together at room temperature	Maintains a relative humidity in 57–60.5% at 25 ∘C; equilibrium moisture adsorption amount is 78.6%; for NO_2 and SO_2 are 227 mg g^{-1} and 288 mg g^{-1}
Acrylate-based copolymer emulsion	[136]	Prepared by emulsion polymerization using main monomers and functional monomers	Showed a large capacity for water absorption (274%)

C_b value was defined as the ratio of humidity amplitude in the steel box lined with material to that in the empty steel box; *B*-value was defined as the function of environmental humidity control.

and type of the PCM and thermal performance of furnishings and appliances indoor. There is no doubt that the PCM will be obtained more attention and applied in more wide areas.

3. Humidity-controlled materials

In addition to the previous analysis, in some coastal cities a lot of buildings suffer from rising damp that high moisture content exists indoors; this is strongly negative for building and indoor furniture not to mention the building built by wooden. High humidity in the indoor air is a well known problem in new buildings which will cause mould growth and an increase of the heating costs [21]. Result showed that the average nighttime humidity was 55–70% throughout the year and was comfortable for the inhabitants in rooms in log and wooden-houses, 38–78%, in some of the reinforced-concrete-building rooms, and 57–72%, when some air-conditioners were used [111]. Anyway, the control of relative humidity to avoid an excessive high or low moisture content existing in the construction is an essential aspect of maintaining indoor air quality, energy performance, and the durability of the building envelope [112]. Many researchers devoted to developing materials in humidity control like as PCM for thermal management.

The indoor humidity can be controlled by the house itself with little or no air conditioning as temperature can be controlled with PCMs. The results showed that it might be possible to reduce energy consumption indoor for heating and cooling by up to 5%

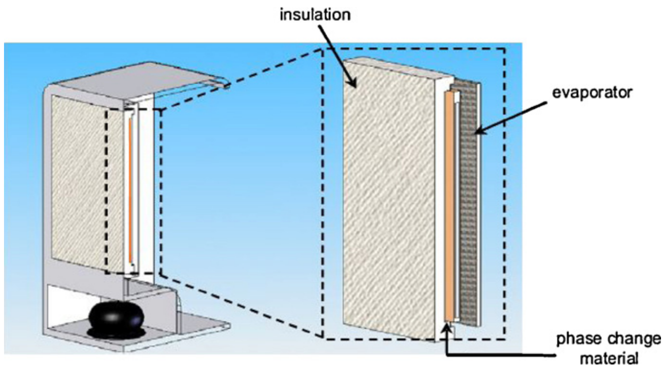

Fig. 2. Schematic presentation of the refrigerator with PCM [110].

and 30%, respectively, when applying hygroscopic materials with well-controlled HVAC systems [113]. The materials which can control humidity are named as humidity-controlled materials, which have been used in applications such as interior wall materials, closets wall material and under floors materials [114]. Humidity-controlled materials with a function of self-operate the humidity indoor with ambient humidity changes [115]. When humidity fluctuates greatly, the humidity-controlled materials can absorb and desorb humidity or keep wet by the driving of humidity [116]. So far, a large amount of humidity-controlled materials can be used to adjust the relative humidity [23,117]. Yan et al. [118] described and tested a new building material when the air relative humidity is 11.3%, 32.8%, 57.6%, 75.3%, 97.3%, and from these tests the sorption isotherms of the building materials can be used to characterize the moisture buffer performance of a material. The humidity-controlled materials applications in building with some main conclusions are summarized in Table 3.

To guarantee a comfortable and healthy indoor climate both thermal management and humidity control are very important. Generally, humidity changes are caused by temperature changes [137,138]. The mechanisms of heat and moisture transferred in materials are so complex that cannot be easily discussed by experiments. In order to analyze the heat and moisture transferred within the building envelope, there are now many numerical models that are capable of describing transfer characteristics [139–143]. Most of the models are not seeking a global understanding of physical and chemical processes. More moderate physical and mathematical details need to further develop. New materials with the function including thermal management and humidity control synchronous are also worth to be expected.

4. Conclusions

Ideal thermal management and humidity control of indoor climate are considered not only to meet the requirements of human thermal comfort but also without or less additional conventional energy. In the last decades, both energy saving latent heat storage and environmental friendly humidity-controlled materials for indoor climate are widely researched and developed.

The micro-encapsulated form-stable composite PCM will attract more attention for thermal management indoor and many works need to further be done in the future including heat transfer enhancement, volume variation controlling, and so on.

The super-efficient and innovative humidity-controlled materials with high moisture absorption and desorption capacity and intelligent self-humidity-control and related key techniques appear a great potential.

More moderate physical and mathematical models and multifunction composite materials containing thermal and humidity control synchronous are worth to be expected.

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